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GRAPHICAL ANALYSIS OF ANNUAL CROP RESPONSE TO FERTILISER APPLICATION

H. VAN KEULEN

Centre for Agrobiological Research (CABO), Wageningen, and Centre for World Food Studies (SOW), Wageningen, Amsterdam, The Netherlands

SUMMARY

The effect of fertiliser application on crop yield is described by the interactive effects of two relations: that between fertiliser application and fertiliser uptake (the recovery of fertiliser) and that between nutrient uptake and yield. It is argued that the latter relation is invariable for a given combination of crop species and plant nutrient, as illustrated for nitrogen on bunded rice. Virtually all variability in application–yield relations results from differences in the parameter values characterising the relation between nutrient application and nutrient uptake.

The uniqueness of the uptake–yield relation permits its use in the determination of nutrient recovery from measured application–yield data. The use of this procedure to formulate fertiliser recommendations for specific situations is discussed.

INTRODUCTION

In the agricultural production process, the individual farmer is constantly faced with the problem of allocating highly variable resources in a meaningful way. Attempts have often been made to describe this process in the form of so-called production functions, which express the yield obtained (Y) as a function of inputs used:

$$Y = f(x, y, z, \ldots.)$$

where x, y, z represent production factors, like the amount of water, minerals or labour. It has become increasingly clear, however, that such attempts are only successful in very simple situations. In somewhat more complex systems there is no unique solution to the production function, since there are many bio-technically

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feasible input mixes that will produce a certain yield, and it is questionable whether these are all agronomically feasible at the same time.

An alternative way of treating the problem is that of developing dynamic production models, that are based on detailed knowledge of crop properties and conditions under which they grow. A number of such models have been developed (van Keulen, 1975; de Wit *et al.*, 1978), but their degree of sophistication is too high to permit application in a more general framework. A short cut between both approaches may be found by using an hierarchical approach in which the yield is, on the one hand, considered as a dependent variable, governed by crop species and environmental conditions, and, on the other hand, as an independent variable, dictating a feasible input combination which will lead to realisation of that predetermined level (van Keulen & de Wit, 1981). The required inputs may, in a schematical way, be distinguished in fieldwork and material inputs, the latter being again subdivided in yield-protecting materials (biocides) and yield-increasing materials (water, nutrients, etc.). This paper specifically deals with the determination of the requirement for the plant nutrient nitrogen for different yield levels.

FERTILISERS AND PLANT PRODUCTION

Apart from water and light energy, plants require inorganic ions to build structural organic material. In the course of time more and more elements have been shown to be indispensable for proper plant growth. This paper mainly deals with nitrogen which was one of the first elements to be recognised as essential and still maintains a special position, owing to the quantities in which it is needed, its high mobility in the soil–plant–atmosphere system and, to some extent, its price. The latter argument is not (yet) decisive in most well-developed countries, but it is a serious impediment for the introduction of more fertilisers in many less-developed countries. It is therefore important that the fertiliser that is being applied is used as efficiently as possible. In this respect it is important to realise that an increased economic yield, as a result of fertiliser application, requires, first, that the applied element is being taken up by the crop and, secondly, that it is utilised to produce the demanded plant parts. Lack of response to fertiliser application may thus be due to the fact that the element has not been taken up, because it was applied at the wrong time, in the wrong place or in the wrong form, or that after uptake it did not express itself in increased economic yield. The latter may be inhibited by other growth-limiting factors such as shortage of water or mineral elements, other than the one applied. The common way of presenting the results of fertiliser experiments showing the yield response as a function of fertiliser applied (Fig. 1) makes it impossible to distinguish between these two possible reasons for a lack of response. The explanatory value of such experiments, and hence their usefulness for extrapolation of results, greatly improves when they are accompanied by chemical analysis of the harvested

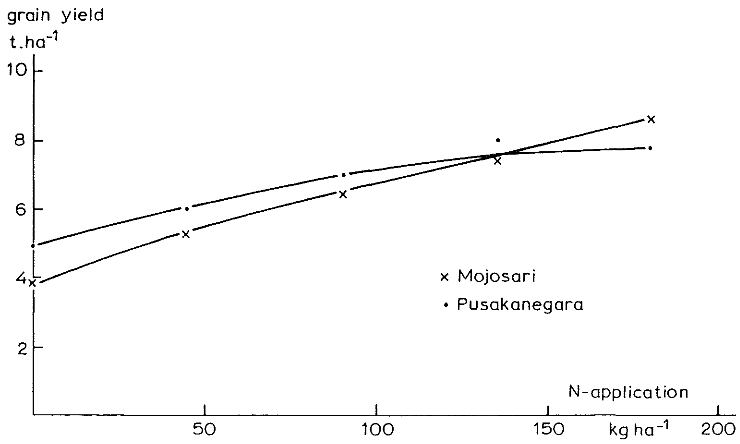

Fig. 1. The relation between nitrogen application and grain yield for bunded rice at two locations on Java (source: Ismunadji *et al.*, 1973).

material. Determination of its composition enables the calculation of the amount of the element taken up by the plant and its subsequent distribution.

Presentation of the results

When, in fertiliser trials, both the yield and the chemical composition of the harvested material have been determined, interpretation of the data is facilitated when the results are presented graphically as suggested by de Wit (1953), and illustrated in Fig. 2. The Figure consists of three graphs. In the first graph (a) the relationship is given between the economic yield and the total amount of the element taken up by the crop. The second graph (b) expresses the uptake of the element as a function of the amount applied. The third graph, constructed from the other two, through the elimination of the uptake, is identical to the one in Fig. 1, giving the relation between fertiliser application and yield.

The yield–uptake curve

The example given here, which is representative for the majority of experiments involving nitrogenous fertilisers, shows that a proportional relation exists between yield and uptake at low uptake values. This linearity indicates that, under conditions where nitrogen is in limited supply, its concentration in the tissue eventually reaches a minimum level, beyond which further dilution or re-mobilisation from vegetative structures is not possible. Each unit of N taken up results in a constant amount of yield being produced. An extensive analysis of yield–uptake relations for a number of crops (van Keulen, 1977; van Keulen & van Heemst, 1981) has shown that the slope of the initial part of the curve is crop-specific and, to a large extent, independent of environmental conditions. Numerical values

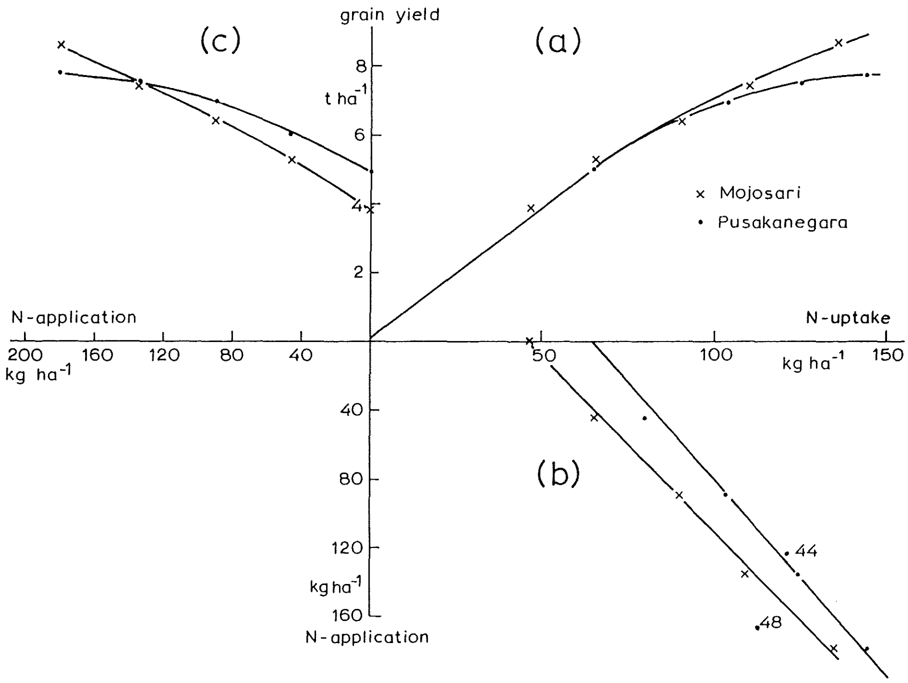

Fig. 2. The relation between total nitrogen uptake and grain yield (a), that between nitrogen application and nitrogen uptake (b) and that between nitrogen application and grain yield (c) for bunded rice at two locations on Java (Ismunadji *et al.*, 1973).

are: 70 kg of grain per kg N taken up for small grains, 100 kg of tuber dry matter per kg N for potatoes and 80 kg of pure sugar per kg N for sugarbeet.

At higher levels of uptake the curve deviates from linearity, reflecting higher concentrations of the element in the tissue, both in the economic plant parts and in the crop residues, at harvest. Finally, the curve levels off, indicating that the element under consideration is no longer a constraint for unrestricted growth. The level of the plateau is determined by the growth factor in short supply and is, in the 'potential growth' situation, a function of the available solar energy during the plant's growth period.

The yield–uptake relation is, in general, independent of the type of fertiliser and the method of application, provided that the fertiliser does not change other growing conditions than the one governed by its main acting element and is not applied so late that a period of serious shortage is followed by one with abundant availability (de Wit, 1953; van Keulen, 1977).

The application–uptake relation

The relation between fertiliser application and total uptake by the crop is, in the example presented in Fig. 2, a straight line over the full range of applications. Again this example is representative for the majority of fertiliser experiments involving nitrogenous fertilisers (van Keulen, 1977; van Keulen & van Heemst, 1981). Of course, when very large amounts of nitrogen fertiliser are applied, the capacity of the vegetation to absorb and synthesise the element may become limiting, resulting in discontinuities in the application–uptake relation (Figs 3(d) and 4(b)).

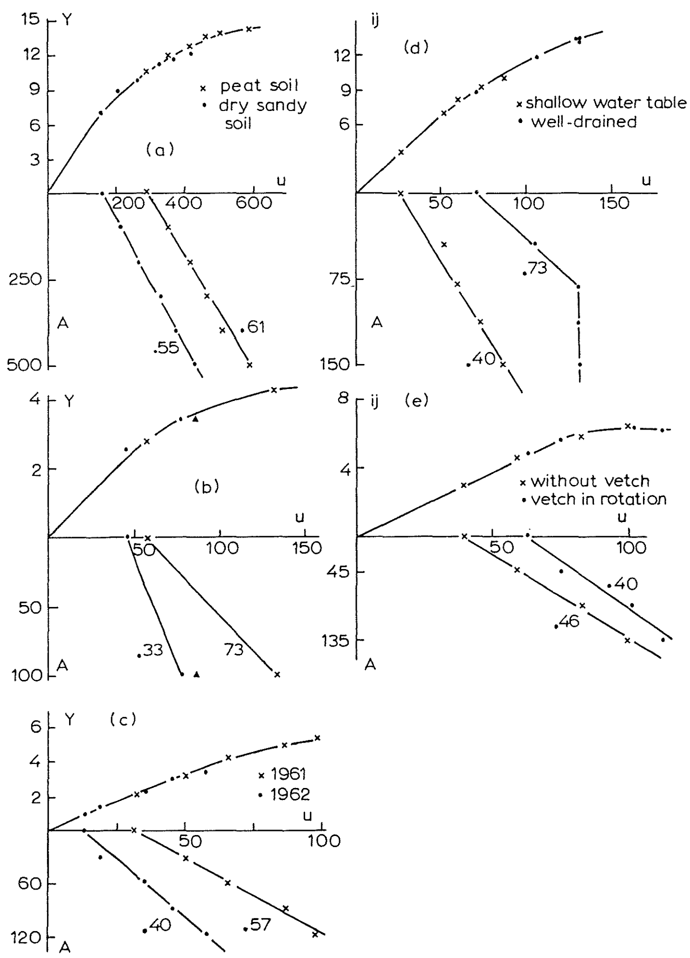

Fig. 3. The relation between nitrogen uptake (U) and yield (Y) and that between nitrogen application (A) and nitrogen uptake. (a) Permanent pasture, The Netherlands (van Steenbergen, 1977) Y in tons dry matter per hectare, U and A in kg N ha^{-1}. (b) Winter wheat, West Germany (Köhnlein, 1972) Y in tons of grain per hectare (15% moisture), U and A in kg N ha^{-1}. (c) Permanent pasture, The Netherlands (Oostendorp, 1964). Y in tons dry matter per hectare, U and A in kg N ha^{-1}. (d) Winter wheat, The Netherlands (Sieben, 1974). Y in tons of grain per hectare (15% moisture), U and A in kg N ha^{-1}. (e) Flooded rice, USA (Williams *et al.*, 1972) Y in tons of grain per hectare, U and A in kg N ha^{-1}.

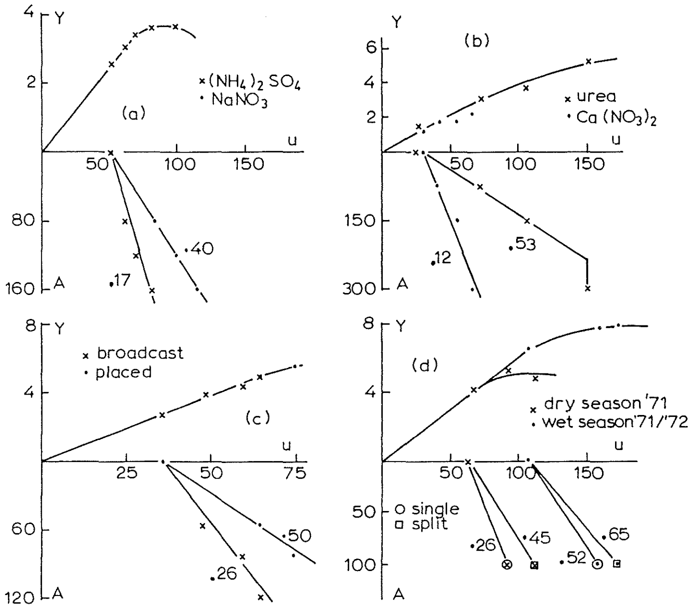

Fig. 4. The relation between nitrogen uptake (U) and yield (Y) and that between nitrogen application (A) and nitrogen uptake. (a) Winter wheat, The Netherlands (Lehr, 1950) Y in tons of grain per hectare, U and A in kg N ha^{-1}. (b) Unimproved pasture, Mali (Penning de Vries *et al.*, 1981.) Y in tons dry matter per hectare, U and A in kg N ha^{-1}. (c) Bunded rice, Java, Indonesia (Ismunadji & Sysmiati, 1976) Y in tons of grain per hectare (15 % moisture), U and A in kg N ha^{-1}. (d) Bunded rice, Sri Lanka (Nagarajah *et al.*, 1975) Y in tons of grain per hectare, U and A in kg N ha^{-1}.

Such a straight line is characterised by two parameters, the intercept with the uptake axis and the slope with respect to the vertical. The first parameter represents the inherent fertility of the soil for the element concerned, the latter the recovery fraction of the applied fertiliser. Both parameters show widely varying values. The uptake at zero fertiliser application is, on the one hand, a soil characteristic, governed by the quantity and quality of the organic matter present in the soil. It is, on the other hand, influenced by environmental conditions, notably soil temperature and soil moisture conditions, which govern the rate of decomposition of the organic material and the ultimate fate of the nitrogen mineralised or immobilised during this process. Finally, management has an influence on its value, through the level of soil reclamation, crop rotation and previous fertiliser applications. In the framework of this paper it is impossible to treat all these aspects exhaustively but some examples are presented in Fig. 3. Figure 3(a) relates to permanent pasture in the Netherlands and shows the influence of soil type on N absorption in the absence of fertiliser application. The sandy soil, with a relatively low organic matter content, supplied ± 160 kg N ha^{-1} year^{-1}, the high value being the result of the application of farmyard manure on all experimental plots, whereas, from the peat soil, with a high organic matter content, almost 300 kg ha^{-1} year^{-1} was extracted. The influence of environmental factors is illustrated in Figs 3(b) and 3(c), referring to an experiment with winter wheat in West Germany and to permanent pasture in the Netherlands, respectively. In the winter wheat, complete interception of winter rainfall by protective shelters increased the uptake of nitrogen in the non-fertilised situation by $\pm 30\%$, presumably because leaching of the mineralised nitrogen beyond the root zone was prevented. Figure 3(c) shows the combined effect of temperature and soil moisture. Spring in 1961 was relatively warm, conducive to rapid mineralisation and relatively dry, again preventing losses by leaching and possibly denitrification. Conditions were reversed in the spring of 1962, which was cold and wet, thus leading to a reduction of over 50% in availability of native nitrogen.

An aspect of management is illustrated in Fig. 3(d) where land improvement by drainage of a field of winter wheat increased the availability of nitrogen in the non-fertilised situation from about 30 to about 70 kg N ha^{-1}, primarily through reduction of denitrification losses, but possibly also by enhancing root activity. The influence of crop rotation is shown in Fig. 3(e), referring to rice, grown in the US, where incorporation of a fall-sown crop of vetch into the soil increased the uptake of nitrogen from natural sources by about 50%. These examples may serve to illustrate that the actual amount of nitrogen from natural sources that will be available to the crop during its growth cycle may vary widely. Prediction of that amount requires detailed knowledge of soil characteristics, environmental conditions and management practice for any given situation.

The proportion of the applied nitrogen fertiliser that is taken up by the vegetation is partly influenced by the same conditions affecting the level of nitrogen uptake at zero-fertiliser application, since processes that render the element unavailable for uptake by the plant act in identical ways on native nitrogen and on nitrogen applied as fertiliser. This phenomenon is easily recognised in the examples presented in Fig. 3 where, in all but one case, higher uptake of soil N is associated with a higher recovery of the applied fertiliser. For fertiliser application on temperate pasture the same conclusion was reached by Brockman *et al.* (1971).

Apart from this, fertiliser recovery may be influenced by the type of fertiliser used, as illustrated in Figs 4(a) and (b) for two contrasting situations. The winter wheat crop of Fig. 4(a), growing in the reclaimed polders of the Zuyderzee, absorbed the nitrate fertiliser 2·5 times as efficiently as the ammoniacal fertiliser. This is the result of ammonia losses due to volatilisation on the lime-rich gritty clay soil (pH 8·2) in these polders. The natural vegetation of Fig. 4(b), growing on a heavy clay soil in the Sahelian region, utilised the nitrate fertiliser far less efficiently than urea. Here the major cause of losses is denitrification, during temporary flooding of the area due to run-on during high-intensity rain showers.

Fertiliser efficiency may also be influenced by timing and method of application. The effect of method of application is illustrated in Fig. 4(c), referring to bunded rice growing on the island of Java. Placement of urea fertiliser as mudballs, at transplanting, directly into the reduced soil layer, prevents the transformation of ammonium into nitrates and the subsequent loss through denitrification. When urea is broadcast onto the layer of standing water, nitrification takes place in the aerobic environment of the water, after which the nitrates, by mass flow or diffusion, enter the reduced soil layer where rapid denitrification follows; hence a much lower availability of nitrogen for the vegetation. Split application of the total amount of nitrogen fertiliser generally leads to higher recoveries since the *rate* of nitrogen uptake by the vegetation is higher at later growth stages, resulting in shorter residence times of the element in the soil solution and hence less losses. This phenomenon is illustrated in Fig. 4(d) referring to bunded rice from Sri Lanka. (By the nature of the experimental technique employed to study the effect of split fertiliser applications, the recovery fractions are based on one application rate only here.)

The recovery fractions determined in a single experiment in a particular year may not be used indiscriminately to illustrate the losses of fertiliser nitrogen. In some cases (denitrification, volatilisation) the complement of the recovered fertiliser may be irreversibly lost from the system. In other situations, however, part of the originally added fertiliser may have been incorporated temporarily in the soil organic matter and may become available in subsequent years.

Conclusions

From the discussion presented in this section it may be concluded that most of the variability in fertiliser application–yield relationships for a given crop is the result of variations in the application–uptake relation. In the examples of Figs. 3 and 4, widely different values of the two parameters characterising the latter relation result, in each case, in a unique uptake–yield function. Causal relationships for a particular type of crop response to fertiliser application can only be established when all three relations can be constructed, i.e. when yield, as well as element content of the crop, is determined: and knowledge of those cause-and-effect relations is necessary in order to judge the scope for improvement and to take the appropriate measures.

APPLICATION OF THE THEORY FOR FERTILISER RECOMMENDATIONS

Analysis of past experiments

In the previous section the conclusion was drawn that, for proper interpretation, fertiliser experiments should be followed by chemical analysis of the various plant parts. That, however, does not imply that the results of past experiments cannot be put to use. Curves as presented in quadrant (c) of Fig. 2 are available in considerable quantities at least for the major crops in a given region. It was argued in the section above on the yield–uptake curve that the initial part of the uptake–yield relation is a crop constant, while the plateau level may be calculated from environmental conditions when it is assumed that the potential growth situation exists (van Keulen, 1976). This implies that the uptake–yield curve for a given combination of crop and environment may be constructed when climatic data are available in sufficient detail (van Heemst *et al.*, 1978). Combination of the application–yield curve with the theoretical uptake–yield function results in the application–uptake curve (Fig. 5).

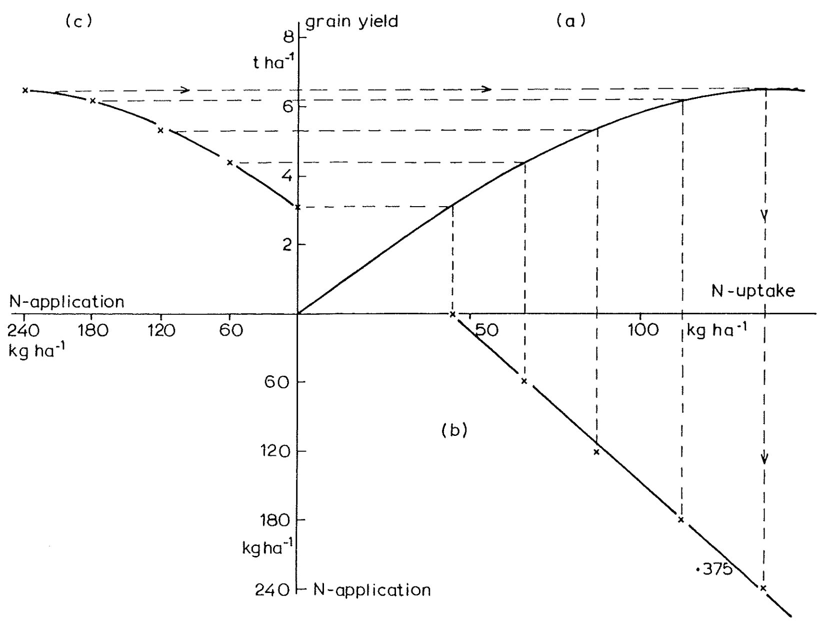

Fig. 5. Graphical illustration of the method used to determine application–uptake relations (b) from measured yield–application relations (c).

The same procedure was applied to some of the data presented by Fagi & De Datta (1981) on flooded rice grown at IRRI in the Philippines. The nitrogen–response curves for the April and June harvests of the variety IR 28 are produced in Fig. 6(c). The (hypothetical) uptake–yield curve (Fig. 6(a)) was constructed with an initial slope of 70 kg grain (at 15 % moisture content) per kilogram of nitrogen absorbed, while the potential grain yield was calculated by the procedure described by van Keulen (1976) employing long term-average radiation and temperature data for Los Baños. Combination of the graphs in Figs. 6(c) and 6(a) yields the points given in Fig. 6(b). The average recovery fractions for the two trials are 0·36 and 0·26 which compare favourably with the experimentally determined values of 0·40 and 0·24, respectively (Fagi, 1977). No actual data on nitrogen uptake are given, so that these cannot be directly compared. Similar results are obtained from other experiments, thus adding to the procedure described.

The available experiments pertaining to nitrogen application to bunded rice for various experimental stations on the island of Java in Indonesia were analysed in this way, which yielded a reasonable number of recovery fractions per location. The numerical values obtained show a wide variation, as could be expected from the evidence presented above in the section on the application–uptake relation. It

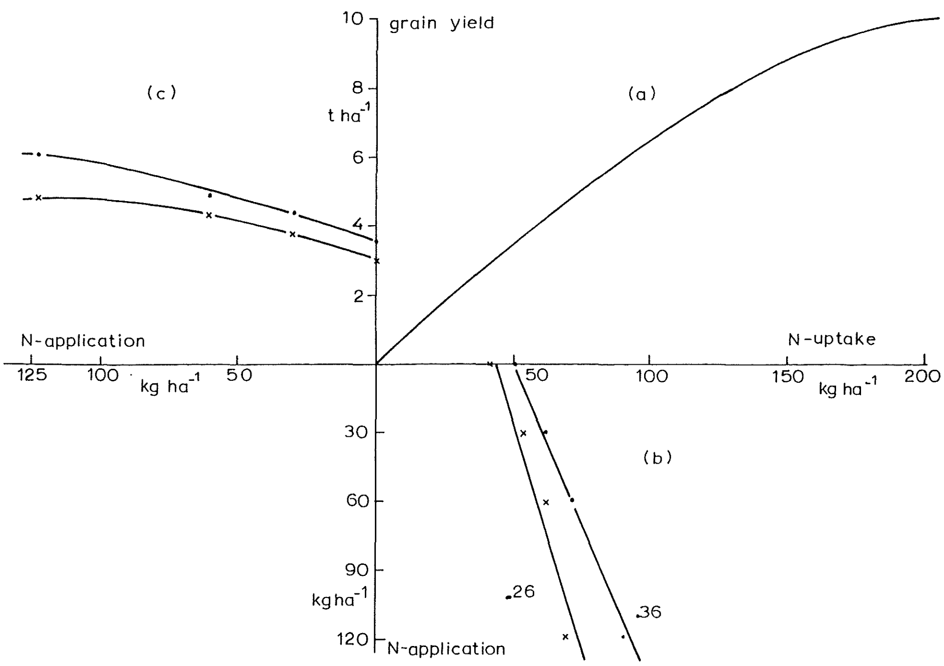

Fig. 6. Application–uptake relations (b) for two plantings of the variety IR28 grown at IRRI, The Philippines, determined from measured yield–application relations (Fagi & De Datta, 1981).

turned out, however, that, for a similar growing period (that is, either the wet or the dry season), and a given location, the recovery fractions show a normal distribution (Fig. 7). In the light of the arguments presented above it may be concluded that the expectation value is mainly determined by the method of application and its timing, whereas the deviations are largely the result of varying environmental conditions: variations in amount and pattern of rainfall, temperature fluctuations, etc. Variations between locations must be attributed to differences in both environmental and soil conditions and must therefore be taken at face value (van Keulen, 1977).

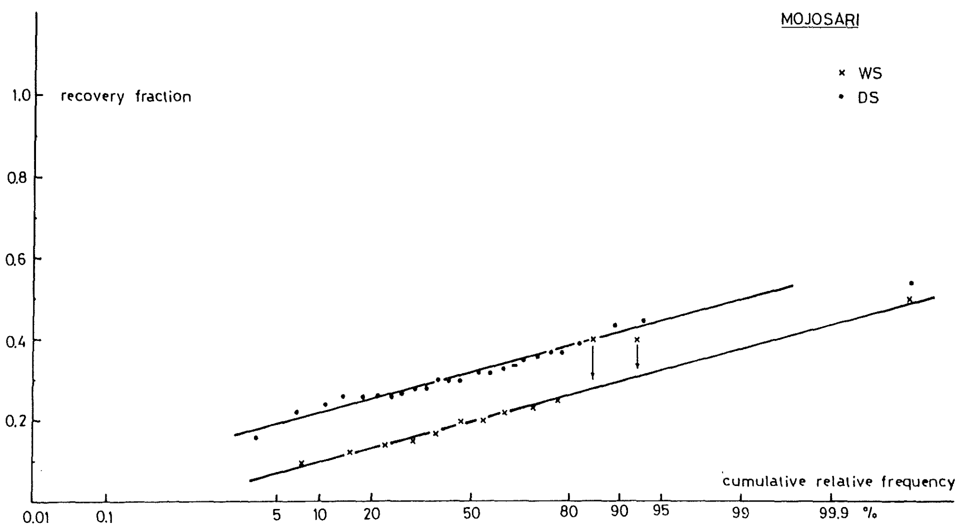

Fig. 7. Cumulative relative frequency distribution of recovery fractions of nitrogenous fertilisers, applied to bunded rice in Mojosari (East Java, Indonesia) in the dry (DS) and the wet (WS) season.

Fertiliser recommendations

The analysis presented so far may now be used to provide fertiliser recommendations for specific situations.

The procedure is illustrated in Fig. 8, again for bunded rice: the starting point is the uptake–yield curve for a given combination of weather and rice variety (van Keulen, 1976). For the application–uptake relation use may be made of local knowledge about yield expectations without fertiliser application, which yields the intercept with the uptake axis as may be deduced from the examples given in Fig. 3. This is the most difficult part of the analysis since non-predictable weather conditions may affect that value appreciably. However, no matter in which way fertiliser recommendations are generated, an estimate of the N supply from natural sources has to be provided. An analysis as described in the previous section provides the slope of the uptake–application curve. For the decision whether or not to apply fertiliser at all, the linear part of the uptake–yield curve may be used, in combination with the most unfavourable conditions in terms of recovery, which for bunded rice is $\pm 10\%$. This implies that a price ratio between fertiliser nitrogen and rice grain of less than 7 (1 kg N applied = 0·1 kg N taken up = 7 kg rice grain produced) makes N application profitable. To decide on the actual amount to be applied, the expected recovery fraction may be used. When the actual recovery fraction in an individual case would be much higher than the one expected, the farmer would be tempted to apply too much fertiliser, which, in the most unfavourable situation, would lead to yield depressions due to lodging or increased susceptibility to pests and diseases and that at higher costs of inputs. The recovery fraction to be applied for a certain region may

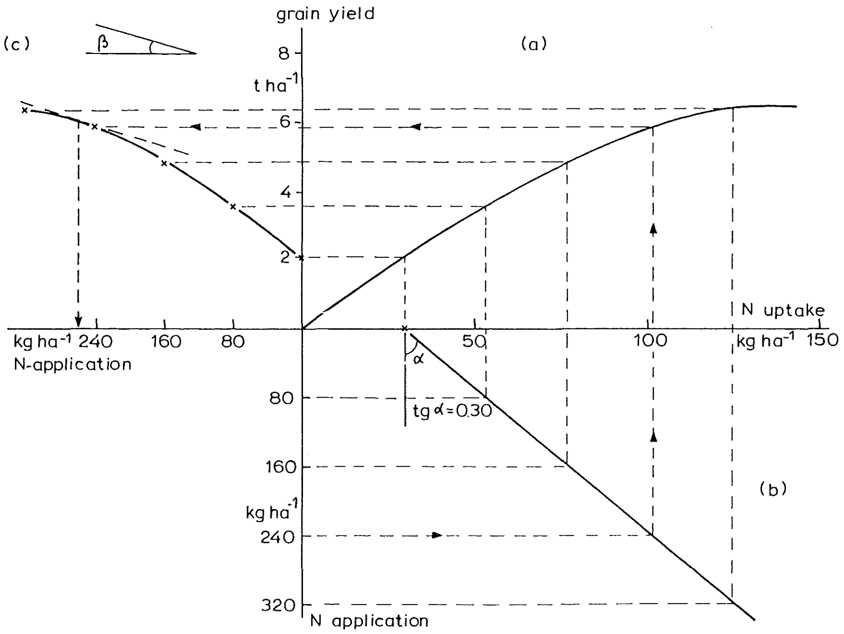

Fig. 8. Graphical illustration of the method to determine optimum fertiliser application rates.

be determined, therefore, as the expectation value minus twice its standard deviation, which reduces the risk of a higher actual value to less than 10%.

Combination of the uptake–yield relation with the application–uptake relation derived in this way permits the construction of the application–yield curve for specific situations (Fig. 8(c)). The optimum amount of fertiliser to be applied may now be determined by combining this curve with the prevalent ratio between output and input (β in Fig. 8(c)). At the point where the slopes are equal, the marginal application rate is found.

The procedure outlined here leads to the use of a price ratio, which leaves sufficient incentives for the farmer to apply nitrogen, while the risk of over-fertilisation is minimised.

APPLICATION IN THE AGRICULTURAL SYSTEMS APPROACH

For application of the analysis in the framework of the hierarchical approach, discussed by van Keulen & de Wit (1981), in principle a similar procedure is used. When the desired or expected yield has been determined on the basis of crop properties and environmental conditions, the nitrogen requirement can be estimated from the uptake–yield curve. The next step is the assessment of the natural soil fertility; that is, the amount of nitrogen available from natural sources. Both soil properties and environmental conditions influence that amount. Finally, the expected recovery of applied fertiliser has to be estimated. This is a function of method and time of application but is also influenced by the reclamation level of the soil: for instance, much larger losses are expected under conditions where temporary waterlogging may occur as a result of insufficient drainage capacity.

For a quantitative assessment of the required parameters, simulation models are being developed (Seligman & van Keulen, 1981), but these are as yet hardly sufficiently rigid to permit application under widely varying conditions. It is to be expected, therefore, that for the time being use must be made of (semi-) empirical relations, based on analogy.

REFERENCES

BROCKMAN, J. S., ROPE, C. M. & STEVENS, M. T. (1971). A mathematical relationship between nitrogen input and output in cut grass swards, *J. Br. Grassld. Soc.*, **26**, 75–7.

FAGI, A. M. (1977). *Environmental factors affecting fertiliser nitrogen efficiency in flooded tropical rice.* MSc Thesis, UPLB, Los Baños, Philippines.

FAGI, A. M. & DE DATTA, S. K. (1981). Environmental factors affecting nitrogen efficiency in flooded tropical rice. *Fert. Res.*, **2**, 53–67.

HEEMST, H. D. J., VAN KEULEN, H. & STOLWIJK, H. (1978). Potential, gross and net production of Netherlands agriculture. *Versl. landbouwk. Onderz.* (Agric. Res. Rep.) 879 (Dutch, with English summary), Pudoc, Wageningen.

ISMUNADJI, M. & SISMIYATI, D. (1976). Studies on fertilizer nitrogen efficiency in lowland rice on an acid latosol in Indonesië. Paper presented at IRRI Annual Conference, April 12–15, 1976.

ISMUNADJI, M., ZULKARNAINI, I., PRAWIROSAMUDRA, A. & YAZAWA, F. (1973). Productivity of some major Java soils, with special reference to yield and nitrogen nutrition of lowland rice. *Contr. Centr. Res. Inst. Agric. Bogor*, No. 7, 17 pp.

KEULEN, H. VAN (1975). Simulation of water use and herbage growth in arid regions. *Simulation Monographs*, Pudoc, Wageningen, 176 pp.

KEULEN, H. VAN (1976). A calculation method for potential rice production. *Contr. Centr. Res. Inst. Agric. Bogor*. No. 21, 26 pp.

KEULEN, H. VAN (1977). Nitrogen requirements of rice, with special reference to Java. *Contr. Centr. Res. Inst. Agric. Bogor*. No. 30, 67 pp.

KEULEN, H. VAN & DE WIT, C. T. (1981). A hierarchical approach to agricultural production modelling. *Proc. IIASA workshop, Environmental Impact of Agriculture, IIASA, Vienna.* (In press).

KEULEN, H. VAN & HEEMST, H. D. J. VAN (1981). Crop response to the supply of macro nutrients. *Versl. landbouwk. Onderz*. (Agric. Res. Rep.), 916, Pudoc, Wageningen.

KÖHNLEIN, J. (1972). Einfluss der winterlichen Stickstoffausswaschung auf die Stickstoffversorgung des Getreides. Untersuchungen auf lehmiger Parabraunerde in Schleswig-Holstein. *Landw. Forschung*, **25**, 1–15.

LEHR, J. J. (1950). Differences in the recovery of nitrogen from ammoniacal and nitrate sources in the reclaimed polders of the Zuyder Zee. *Plant and Soil*, **2**, 345–57.

NAGARAJAH, S., JAUFFER, M. M. M. & WILLENBERG, S. M. (1975). Timing of nitrogen application—Its effect on nitrogen utilization and protein content of rice. *Plant and Soil*, **42**, 349–58.

OOSTENDORP, D. (1964). Stikstofbemesting en grasgroei in het voorjaar. *Landbouwk. Tijdschr.*, **76**, 101–10.

PENNING DE VRIES, F. W. T., KRUL, J. M. & VAN KEULEN, H. (1981). Productivity of Sahelian rangelands in relation to the availability of nitrogen and phosphorus from the soil. '*Nitrogen cycling in West-African ecosystems*', SCOPE/UNEP International Nitrogen Unit, Royal Swedish Academy of Sciences, Stockholm, pp. 95–113.

SELIGMAN, N. G. & VAN KEULEN, H. (1981). PAPRAN: A simulation model of annual pasture production, limited by rainfall and nitrogen. In *Simulation of nitrogen behaviour of soil-plant systems* (Frissel, M. J. & van Veen, J. A. (Eds.). Pudoc, Wageningen.

SIEBEN, W. H. (1974). Over de invloed van de ontwatering op de stikstoflevering en de opbrengst van jonge zavelgronden in de IJsselmeer-polders. *Van Zee tot Land* No. 51.

STEENBERGEN, T. VAN (1977). Invloed van grondsoort en jaar op het effect van stikstofbemesting op de graslandopbrengst. *Stikstof*, **85**, 9–15.

WILLIAMS, N. A., MORE, M. D. & RUCKMAN, J. R. (1972). Burning versus incorporation of rice crop residues. *Agron. J.*, **64**, 467–8.

WIT, C. T. DE (1953). A physical theory on placement of fertilizers. *Versl. landbouwk. Onderz.* (Agric. Res. Rep.) 59·4, Staatsdrukkerij, 's-Gravenhage.

WIT, C. T. DE *et al.* (1978). *Simulation of assimilation, respiration and transpiration of crops. Simulation Monographs.* Pudoc, Wageningen.